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WATER STORAGE IN A PL-566 WATERSHED AS AFFECTED
BY STREAM WATER LEVEL CONTROL

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SUMMARY:

A simulation model was developed to predict the
volume of water stored in the soil profile for a
watershed scale drainage project with both con-
trolled and uncontrolled water levels in the main
channel.

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INTRODUCTION

There are about 3.4 million hectares of drained farm land in the South Atlantic Coastal Plain. In North Carolina alone, artificial drainage is needed for agricultural production on about 1 million ha, or 35% of the cropland.

In many areas of the Coastal Plains, field scale drainage systems cannot be installed because of inadequate outlets. Drainage districts have been organized in many watersheds under provisions of Public Law 566 and natural streams have been channelized to provide good drainage outlets. In some cases, drainage improvement and flood control have included deep drainage channels which have satisfied drainage requirements but have caused other problems. An example is the Conetoe Drainage District in Edgecombe and Pitt Counties, North Carolina. Here, deep channels on the Mitchell Creek branch of the watershed have caused overdrainage in the sandy soils near the banks. The rapid drainage provided by these deep canals is needed during wet periods but is excessive during most of the growing season. Water can be replaced by irrigation, but the irrigation water must be obtained from deep wells or from the channels. Channel water supplies are frequently inadequate during dry periods.

One solution that has been proposed for this problem is to use a control structure in the drainage canal that can be lowered to provide rapid drainage during the wet periods and raised during the growing season to prohibit overdrainage and conserve water.

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A cooperative research project between the USDA-ARS, North Carolina State University, the Soil Conservation Service, the Conetoe Creek Drainage District and several local farmers is being conducted on the Mitchell Creek watershed to analyze the effects of controlling the channel stage on water table elevations, amount of water stored in the soil profile and crop response. This paper reports the results of an analysis to determine the effect of water level control in the channel on volume of water stored in the soil profile, the amount of water available for irrigation and water availability to crops.

APPROACH

A schematic of the type of water management system considered is given in Figure 1. When rainfall occurs, water infiltrates at the surface through the profile raising the water table and increasing the drainage rate to the canal. Water may also be removed from the profile by evapotranspiration (ET) lowering the water table and consequently decreasing the drainage rate. The rate that water drains to the canal depends on the water table elevation, the profile depth, the depth of water in the canal and the hydraulic conductivity of the soil.

In case 1, where there is no water level control in the channel, water drains rapidly, especially near the channel banks; the water table is deep and the volume of water stored in the soil profile is small. When the channel stage is controlled (case 2 in Figure 1), we may still have drainage but at a reduced rate. Under these conditions more water is stored in the soil profile. During the dry periods, the water table may be lower in the field than in the canal as shown in Figure 1. In this case water will move from the canal to the soil. This assumes, of course, that drainage from up-stream is sufficient to hold the water level in the channel at the control elevation. If water is pumped from the controlled channel for irrigation or for other uses at a faster rate than it is replinished from upstream, the water level in the canal will be lowered which will increase drainage from the adjacent lands.

The approach for determining the effect of controlling the channel stage, on water available to plants and on the amount of water stored, was to use solutions to the Boussinesq equation to simulate the water table elevation with and without channel control.

The Boussinesq equation may be expressed as:

$$f \frac{\partial h}{\partial t} = \frac{}{x} \left(K h \frac{\partial h}{\partial x} \right) + R$$

where h is the elevation of water table above the datum, t is time, x is the horizontal distance from the channel, f is the drainable porosity, K is the saturated hydraulic conductivity and R the rate of rainfall or irrigation, which is negative for evapotranspiration. Use of the Boussinesq equation is based on the following assumptions:

1. The Dupuit-Forchheimer (D-F) assumptions.
2. Flow in the unsaturated zone is negligible.
3. Water drained from the unsaturated zone is assumed to be instantaneously released as the water table falls.

The Boussinesq equation was written in finite differences form and solved numerically similar to the solution by Skaggs (1975). The finite difference methods were formulated to consider the following variation in boundary conditions and soil properties in order to describe real field situations.

1. The canal stage may be a function of time.
2. Evapotranspiration is assumed to be a function of water table.
3. Drainable porosity is a function of water table depth.
4. The impermeable layer may be sloped at angle α (Figure 1).
5. The soil profile may be layered both horizontally and vertically.
6. The soil surface elevation may vary with distance from the drain, x.

The solution methods as well as the results of field tests of the solution are described in detail by Badr (1983). Using recorded weather data for rainfall and ET, solutions to the Boussinesq equation can be used to simulate the response to channel water level control for a whole season. The solutions predict the water table elevation as a function of time and distance along the aquifer, and calculate the following variables on an hourly basis.

1. Total volume of water in the soil profile,
2. Volume of water stored above a given datum,
3. Upward flux,
4. Evapotranspiration,
5. Rate of drainage to or from the soil profile,
6. Depth of the dry zone,
7. The stress day index, SDI.

The stress day index was calculated from the equation:

$$SDI = \sum_{i=1}^{n} (1 - AET_i/PET_i)$$

Hiler and Clark (1971), where AiT_i and PET_i are the daily actual and potential ET values, respectively, and N is the number of days in the simulation period. The SDI was calculated for each position node (each x value) in the finite difference solutions. Thus, SDI values where predicted for positions ranging from the channel bank (x = o) to a distance of 1200 m away from the channel for all cases simulated.

PROCEDURE

A simulation analysis was conducted to determine the effect of channel water level control on the amount of water stored in a section of the Mitchell Creek study area.

A plan view of the study area located on a two mile section of Mitchell Creek, is shown in Figure 2. A fabridam structure was installed in the spring of 1982. It provides the capability of raising the channel water level by 2.5 m with a maximum elevation of 11.5 m above sea level. Water table elevations over the study area are measured in 50 observation wells distributed along six transects perpendicular to the creek, and extending to about 1200 m on either side of the channel. Forty of the observation wells are equipped with Stevens type F water level recorders. The water levels in the other wells are read on a weekly basis. The stream water level is measured at 13 stream gaging stations equipped with recorders and installed along the stream between the inlet and outlet of the study area. The stream flow is measured on weekly basis at three locations near the inlet, center and the outlet of the study area. A complete soil survey of the study area was conducted and surface elevations determined along each line of observation wells. The saturated hydraulic conductivity and the drainage branch of the soil water characteristic were measured for each layer of each soil type in the area. Relationships for drainage volume, drainable porosity and steady upward flux as functions of water table depth were calculated for each soil type and profile layering sequence and are given in detail by Badr (1983). Climatological data such as rainfall, screened pan evaporation, relative humidity, solar radiation and other variables necessary to calculate potential evapotranspiration are measured at weather stations near the center of the study site (Figure 2).

Water table data from line numbers 4 and 5 (Figure 2) were used to test the validity of the Boussinesq based simulation model for conditions on this watershed. These lines were selected because they are far enough away from lateral ditches, so that those ditches did not influence drainage; i.e.,

water movement was assumed to be perpendicular to the canal. Details of the results of those tests, which showed that water table fluctuations in response to rainfall, ET and channel water level control could be predicted with the model, will be presented by Badr (1983).

The analysis of the effect of channel water level control on the storage and availability of water in the soil profile was conducted for the horizontal section along line number 4 in Figure 2. The profile section considered in the analysis is shown in Figure 3. It is bounded on the left side by the main channel and on the right side by a no flux boundary conditions at a distance of 1350 m from the canal. The no flux boundary condition corresponds to a water divide which was located by observing the water table slope along transect 4. There are three soil series along the transect as shown in Figure 3, Conetoe loam, Portsmouth loamy sand and Portsmouth sandy loam, coarse loamy variant. The saturated hydraulic conductivity of each layer of each series is shown in Figure 3.

Solutions to the Boussinesq equation subject to the channel water level and appropriate boundary conditions (Figure 3) predicts water table elevation with respect to time and position $h = h(x,t)$. The water stored at any time was determined from plots of the drainage volume versus water table depth (Figure 4). The drainage volume is the quantity of water that must be removed from the soil profile to lower the water table from the surface to any given depth. It may be calculated from the soil water characteristic by assuming that the unsaturated zone of the profile is always drained to equilibrium with the water table. The slope of this curve is the drainable porosity. For each distance x in the section profile, the volume of water stored per unit surface area is equal to the saturated volume at that particular location (i.e. the volume corresponding to a water table at the surface) minus the drainage volume corresponding to the predicted water table depth at that distance. The volume was determined for each x and averaged over the transent to determine the total storage in the soil profile at a given time.

Simulations were conducted for the 77 day period, April 13 to June 28 for three years, 1980, 1981 and 1982. The water table response was simulated for conventional drainage, where the canal water elevation was 9.7 m, about 2.8 m from the surface; and for controlled conditions in which the channel water elevation was held at 11.4 m, approximating 1.1 m from the surface, for the entire simulation period.

All of the water stored above the impermeable layer, calculated as described above, could theoretically be pumped out of the surface aquifer for irrigation or other purposes. Since the depth of the aquifer is shallow, however, a large number of the relatively low-yielding wells would be required to make use of the stored water. Current practice is to pump from the drainage channel, which is attractive from an economic point-of-view. When the drainage channel is used as the water source, however, the depth of the channel bottom is the maximum depth that the water table can be lowered. That is, water stored in the profile at depth below the channel bottom is not available. It cannot be removed by pumping from the channel. Therefore, water stored above the elevation of the channel bottom was called available water and was determined by simply subtracting the water stored below that depth from the total water stored above the impermeable layer.

Another important question is, at what rate is the stored water available for irrigation? To answer that question, consider the following senario. Rainfall is plentiful during the early part of the growing season and, due to channel water level control, the profile average storage is high. Then a drought occurs. A part of the watershed is irrigated by pumping from the channel. As long as the pumping rate is less than or equal to the rate entering from upstream, the water level in the channel well remain constant and water stored in the profile will not change much, except where the water table is close enough to the surface for a direct use by plants. As pumping by other upstream users increases or the inflow rate is reduced by other methods (which might include additional water level control upstream), pumping for irrigation will lower the channel water level below the controlled elevation. As the water level in the channels is lowered, seepage from the profile will increase and the stored water, both in the channels and in the soil profile, will be used for irrigation. The desired pumping rate will depend on the amount of land being irrigated. However, the maximum rate that water can be pumped on a continuous basis, will be the rate that water seeps from the profile into the channel when the channel water level is at the bottom. This rate will depend on how much water is stored in the soil profile, with the rate increasing with profile storage. The rate of seepage into the channel per unit surface area across a transect as a function of average profile storage was determined from the simulation. This relationship is shown in Figure 5.

To calculate the volume of water stored in the main stream and lateral ditches, the standard step method described in detail by Ven Te Chow (1959), was used. The volume of water stored as a function of the controlled elevation in the channel is plotted in Figure 6.

RESULTS AND DISCUSSION

Predicted water table profiles at the end of the 77 day simulation period in 1980 are plotted in Figure 7 for both controlled and uncontrolled conditions. The difference in the water table elevations varys from 1.7 m close to the channel to less than 0.2 m at 1200 m from the channel. Not only is much of the water between the two curves shown in Figure 7 removed when the channel water level is not controlled, but more suction is applied and more water removed from the unsaturated zone near the soil surface. This reduces water available to plants even if the water table is too deep for the plants to benefit from upward water movement from the saturated zone.

Predicted water table elevations at a point 96 m from the channel are plotted as a function of time in Figures 8 and 9 for 1980 and 1982, respectively. The initial water table elevation was taken as that observed in the field on April 13 of each year. The water level in the channel was assumed to be raised to 11.43 m on April 13 for the controlled case and allowed to remain at the observed 9.70 m for the uncontrolled case. During the first few days the water table elevation increased due to water movement from the channel for the controlled case and decreased due to drainage for no control. The water table elevations increased due to rainfall and decreased due to drainage for the remainder of the season. However, continued drainage for the uncontrolled case caused difference in water tables to gradually increase with time for both years (Figures 8 and 9).

The predicted amounts of water stored at elevations above that of the channel bottom (9.35 m) are also plotted in Figures 8 and 9 for controlled and uncontrolled conditions. Units are cm or cm^3 per cm^2 of surface area. Recall that this is the amount of water that could be drained from the profile by lowering the water table to the elevation of the channel bottom. Notice that, for both years, controlling the channel water level initially increased the volume of water stored due to subirrigation. However, the big increases in water storage were due to rainfall events such as occurred on days 13-15 in 1982 (Figure 9). Rainfall increased storage for uncontrolled as well as controlled conditions; but the water stored was drained out when the channel was not controlled. [The difference in storage increased gradually with time for both years.] The mechanisms affecting the amount of water stored in the

profile can be analyzed by examining the predicted discharge rate from the soil profile to the channel; i.e. the drainage rate at $x = o$. The predicted drainage rate into the channel is plotted as a function of time for both controlled and uncontrolled channel water levels in Figure 10 for 1980. For controlled conditions, the drainage rate was negative for the first 15 days implying water movement from the channel into the soil profile. It was also negative for brief periods later in the season. During most of the simulation period, however, water moved from the profile into the channel as indicated by the positive drainage rates. However, these drainage rates were always much less than corresponding rates for the uncontrolled conditions in the reduction of drainage outflow rather than water movement from the channel into the soil profile.

The difference in storage volumes between controlled and uncontrolled conditions increased gradually with time for both 1980 and 1982 (Figures 8 and 9). These results show that channel water level control increased the water stored in the profile by 12.5 cm in 1980 and by 15.0 cm in 1982. In addition to increasing storage, channel control also raised water tables and increased water availability to plants. As an example, the predicted ET (averaged over the transect) was 29.2 cm for controlled conditions in 1982 versus 25.5 cm for uncontrolled conditions during the same 77 day simulation period. The increase in ET can be added to the increased storage to give the total amount of water conserved by controlling the water level in the channel. In 1982 this amounted to 15 cm + (29.2 - 25.5) cm = 18.7 cm. Results for increase in storage, ET and total water conserved are summarized for all three years simulated in Table 1.

Although channel water level control increased the predicted storage in the profile by at least 55% in every year, results in Table 1 indicate that more than 20 m [cm?] of water would have been stored in the profile under uncontrolled conditions. This is enough water to supply irrigation needs for most seasons in the North Carolina Coastal Plains. Even though this water is stored at elevations above the bottom of the channel and it would eventually drain to the channel where it could be picked up and used for irrigation, the drainage rate would be too slow for use to supply irrigation needs. It could be removed by a dense network of shallow wells; but this alternative is not attractive to most farmers.

Under controlled conditions, irrigation water can be obtained directly from the channel (Figure 6). When this water is expended, the maximum rate

Table 1. The volume of water saved by the channel control for 1980, 1981 and 1982.

Year	Case	Storage by the end of 77 days cm³/cm²	Increase in storage due to control	Percentage increase	Actual ET in cm	Increase in ET due to control	Water saved by channel control (columns 4+7)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	
1980	No control	21.6			21.0		
	Control	34.1	12.5	58	22.2	1.2	13.70
1981	No control	20.9			23.5		
	Control	33.4	12.5	57	24.5	1.0	13.5
1982	No control	24.6			25.5		
	Control	39.5	14.9	61	29.2	3.7	18.6

that water can be pumped is dependent on the drainage from the profile to the channel. This rate is in turn dependent on the water table elevations and the amount of water stored as shown in Figure 5. Results in Figure 5 show that the drainage rate of 0.25 cm/day (0.25 cm^3/day per cm^2 of surface area) will result from a profile storage of 36.5 cm. This means that as long as the storage is 36.5 cm or greater, water would drain out of the profile fast enough to irrigate the entire transect at a rate of 0.25 cm/day. It follows that the drainage rate would be large enough to irrigate one-half or 50% of the surface area at a rate of 0.5 cm/day. Referring to Figure 7 for 1980, predicted storage under controlled conditions was greater than 36.5 cm at all times after t = 12 days. The amount of water that would drain to the channel at a rate equal to or greater than 0.24 cm/day may be obtained by subtracting 36.5 cm from the storage value plotted in Figure 7. That volume is plotted versus time in Figure 11. Amounts available at drainage rates equal or greater than 0.125 cm/day and 0.05 cm/day are also plotted in Figure 11.

Predicted values of the stress-day-index (SDI) at the end of the 1980 simulation is plotted as a function of distance from the channel in Figure 12. The highest SDI values occurred near the channel for uncontrolled or conventional drainage conditions. The values decreased with distance away from the channel. For controlled conditions, water tables were held close enough to the surface to eliminate stress (SDI = 0) within about 50 m of the channel. SDI values increased rapidly between 60 and 100 m from the channel, primarily because of increases in surface elevations (Figure 3) and a consequent increase in water table depth. For points greater than 500 m from the channel, SDI values decreased with distance. The predicted SDI values at all locations were smaller than those obtained for uncontrolled conditions.

SUMMARY

A simulation model based on numerical solutions to the Boussinesq equation was developed to predict the volume of water stored in the soil profile for a watershed scale drainage project. The volume of stored water was predicted for controlled channel water level conditions and un-controlled conditions. Simulations were conducted for 77 day periods between April 13 and June 27 in 1980, 1981 and 1982. The volume of water stored at elevations above that of the channel bottom was increased by more than 57% in all years by controlling the channel water level at an

elevation 1.7 m higher than the uncontrolled or normal drainage cases. Water controlling the channel water level raised water tables near the channel by 1.7 m, water tables 1200 m from the channel were raised by 0.2 m in 1980. The rate that water will drain from the soil profile into the channel depends on the water table elevations, and thus on the volume of water stored in the profile. The amount of water that could be removed from the profile at rates sufficient to irrigate 10%, 25% and 50% of the watershed area were predicted as a function of time for 1980. The results showed that more than 5 cm of water was available at rates sufficient to irrigate 25% of the land area after day 15 in the 77 day simulation period.

Channel water level control eliminated the drought stress, as predicted by the stress-day-index, within 60 m of the channel. The SDI was reduced by about 22% compared to the uncontrolled conditions, for the remainder of the transect perpendicular to the channel.

REFERENCES

Badr, A. W. 1983. The development and testing of a simulation model for large scale water table control. Ph.D. Thesis, Department of Biological and Agricultural Engineering, N.C. State University, Raleigh. In preparation.

Chow, V. T. 1959. Open channel hydraulics. McGraw-Hill, N.Y. pp. 265-268.

Hiler, E. A. and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Transactions of the ASAE, 14(4):757-761.

Skaggs, R. W. 1975. Drawdown solutions for simultaneous drainage and ET. J. Irr. Drain. Div., ASCE, 101:279-291.

No flux boundary conditions

Soil Surface

WATER TABLE

Case 2

Case 1

Impermeable layer
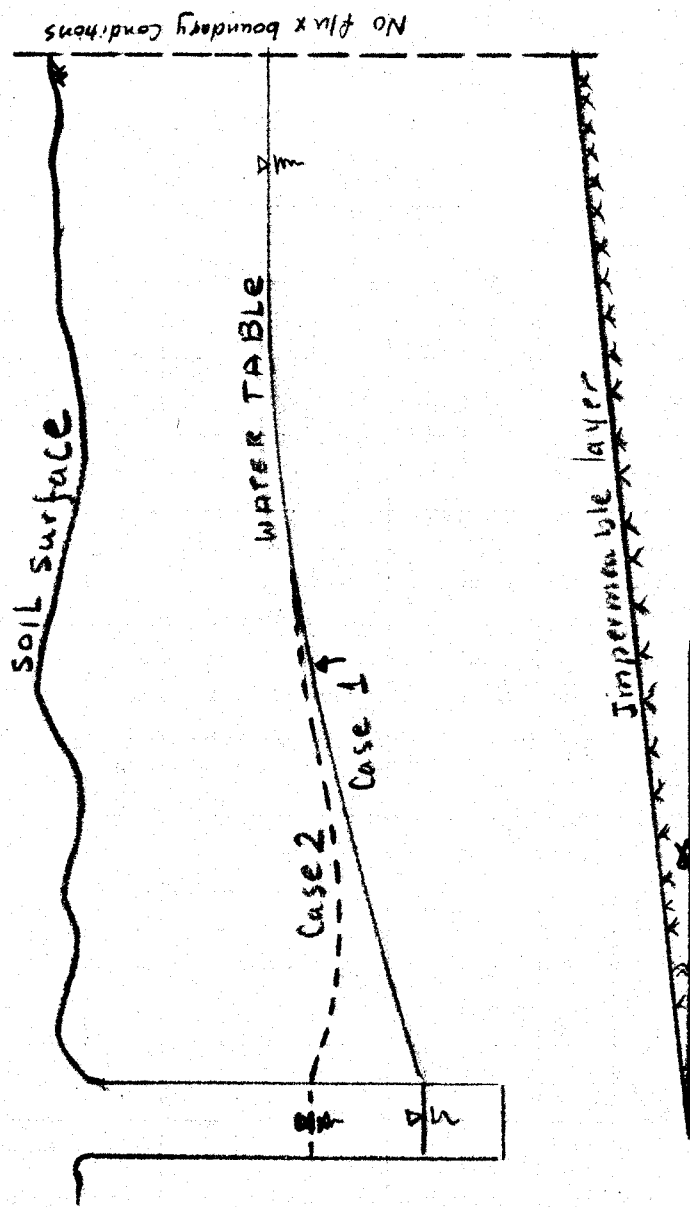
Figure 1: Schematic of Water Management System
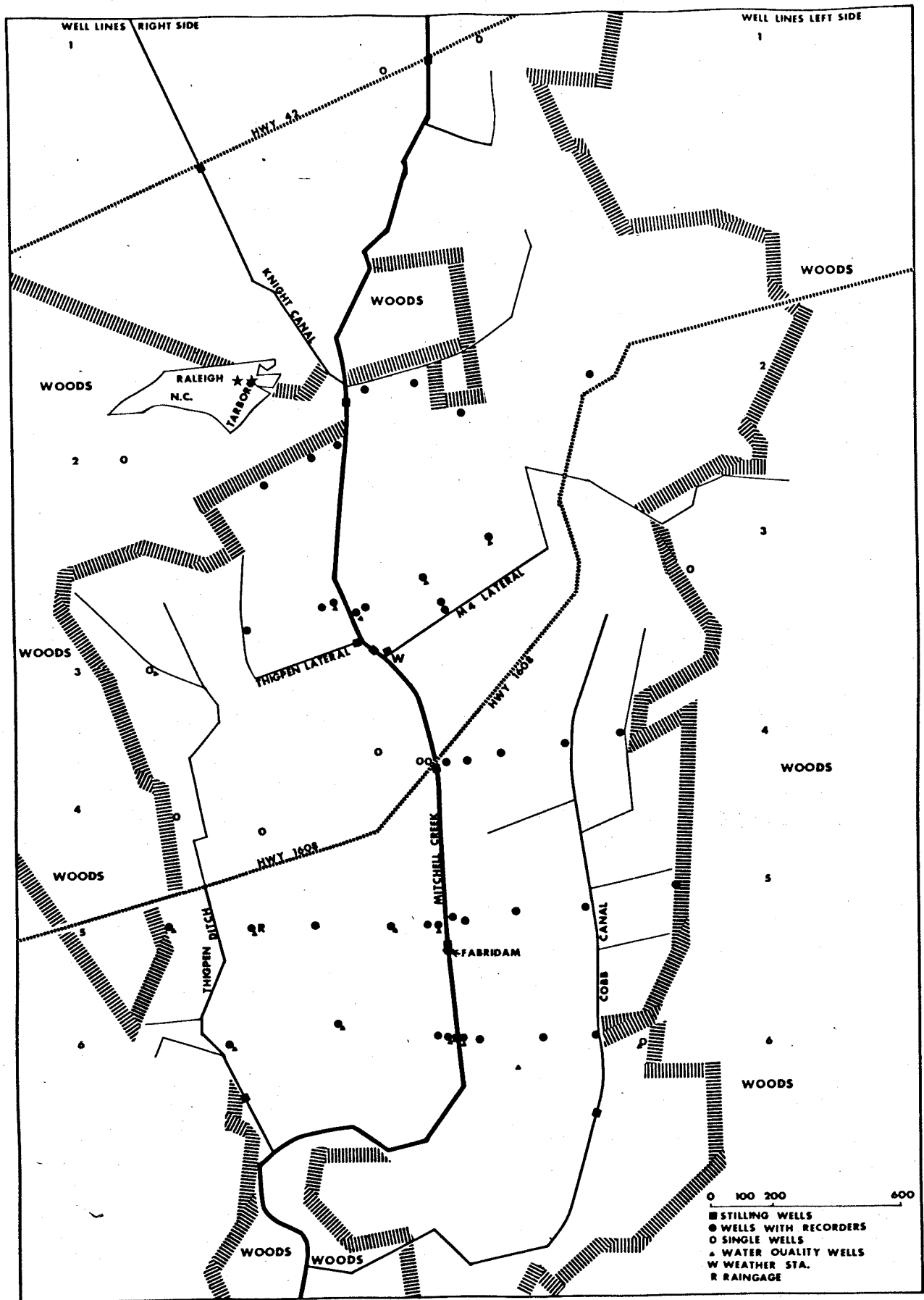
Figure 2. Project sketch of Mitchell Creek Study showing
Channel Systems and Equipment locations.
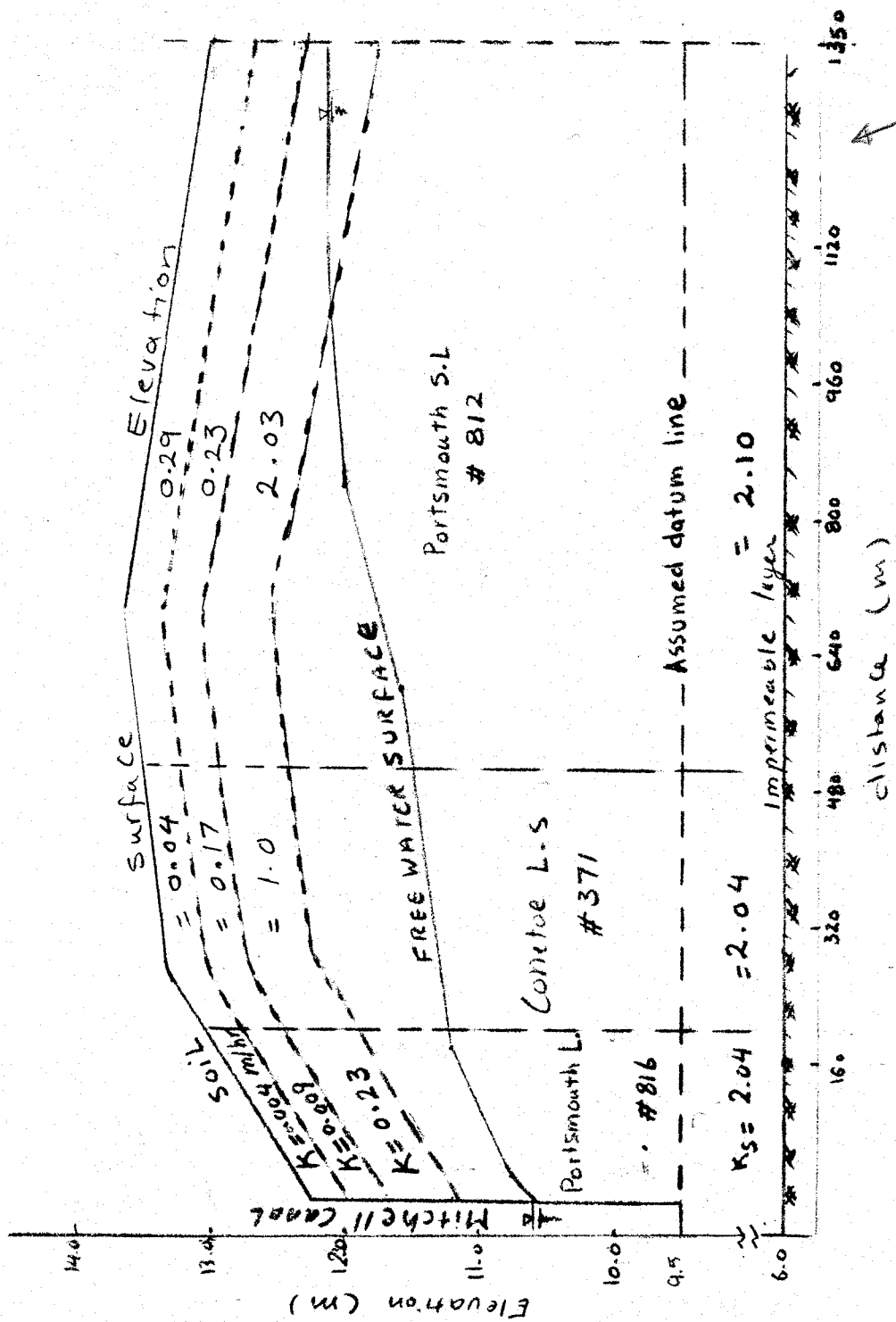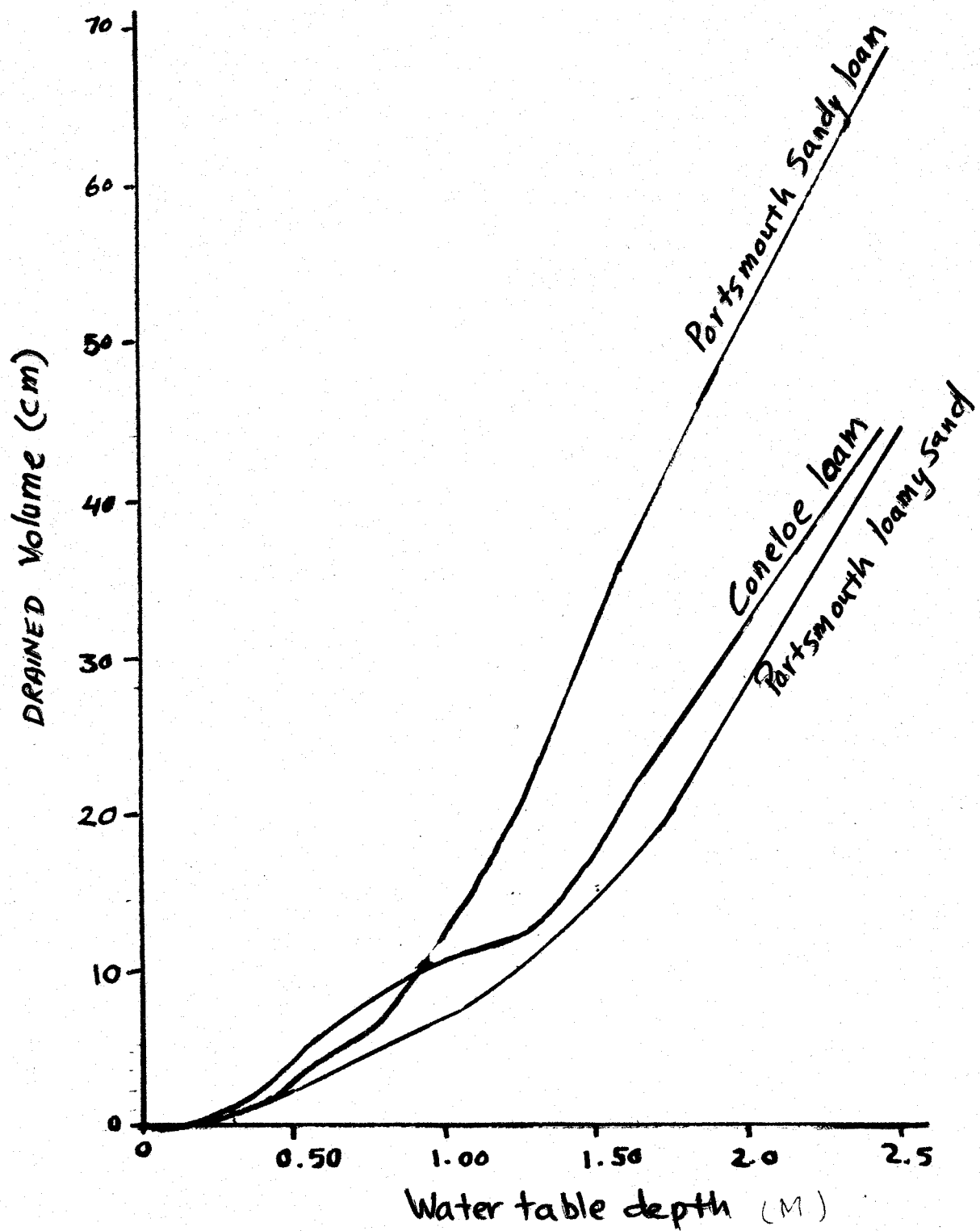
FIGURE 3. Observation well line #4 profile section.

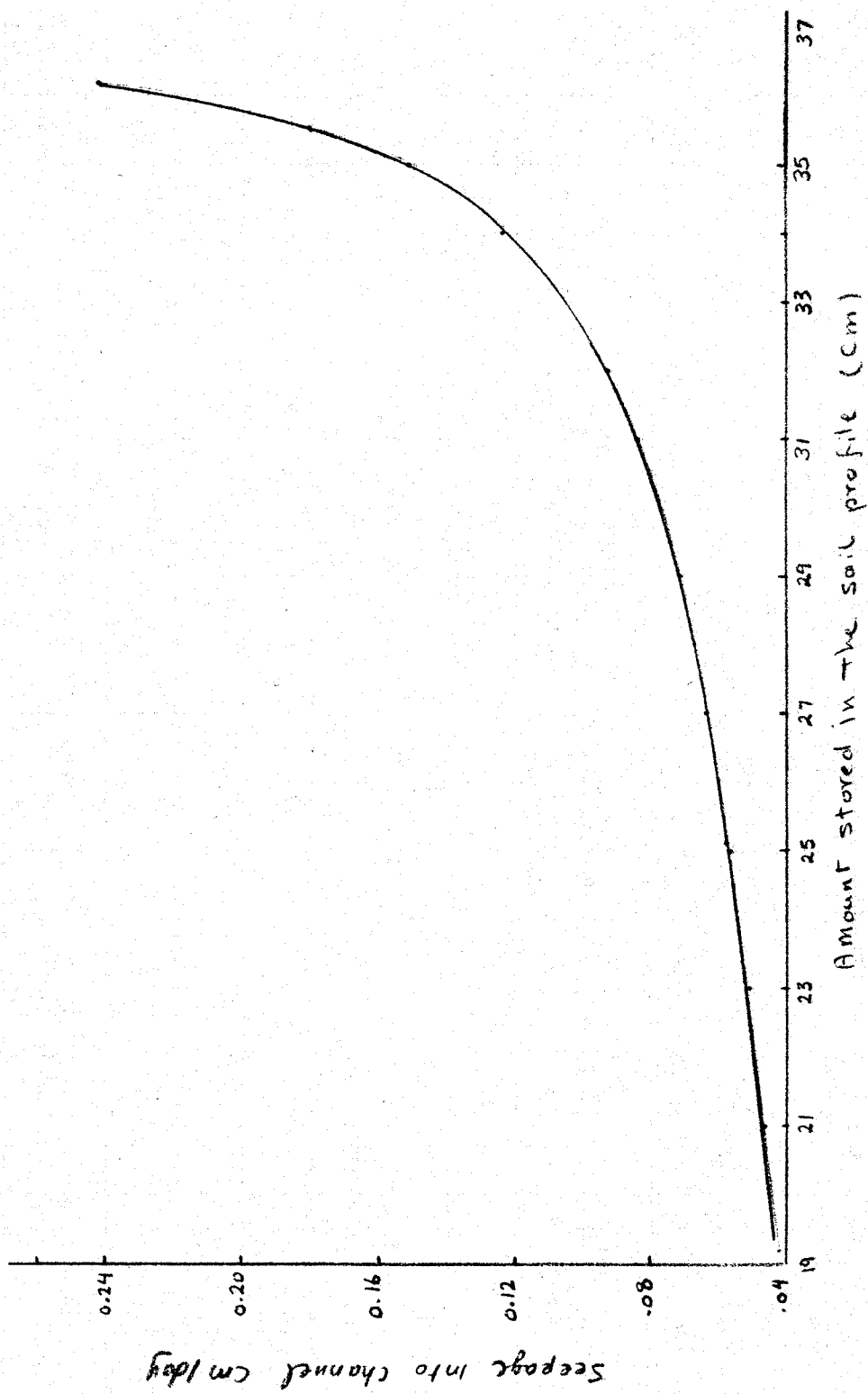Figure 4: The drained volume versus water table depth for the three soil series were used in line #4

Figure 5: The seepage rate into the channel per unit surface area versus the amount of water stored in the soil profile
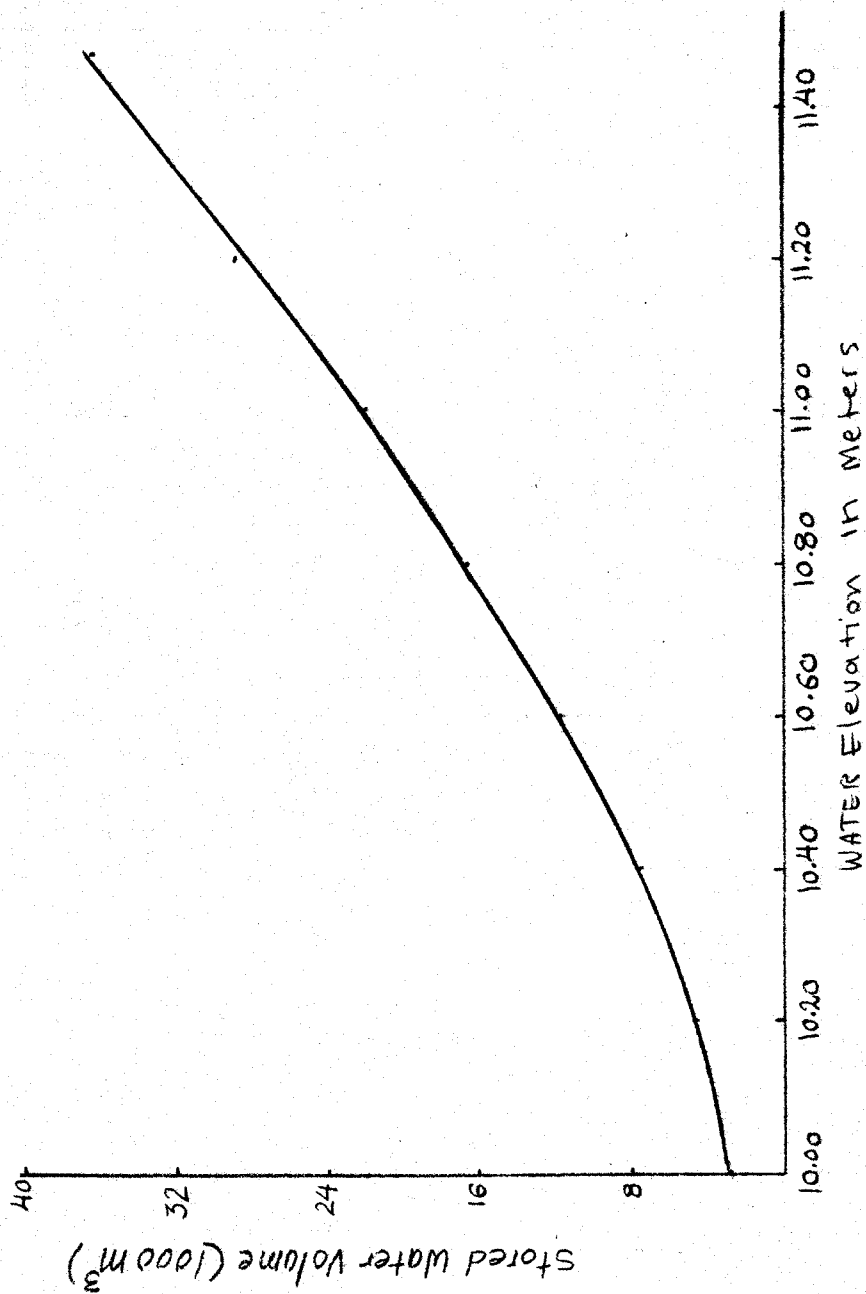
Figure 6. The volume of stored water in the main channel and lateral ditches versus the water elevation in front of the structure
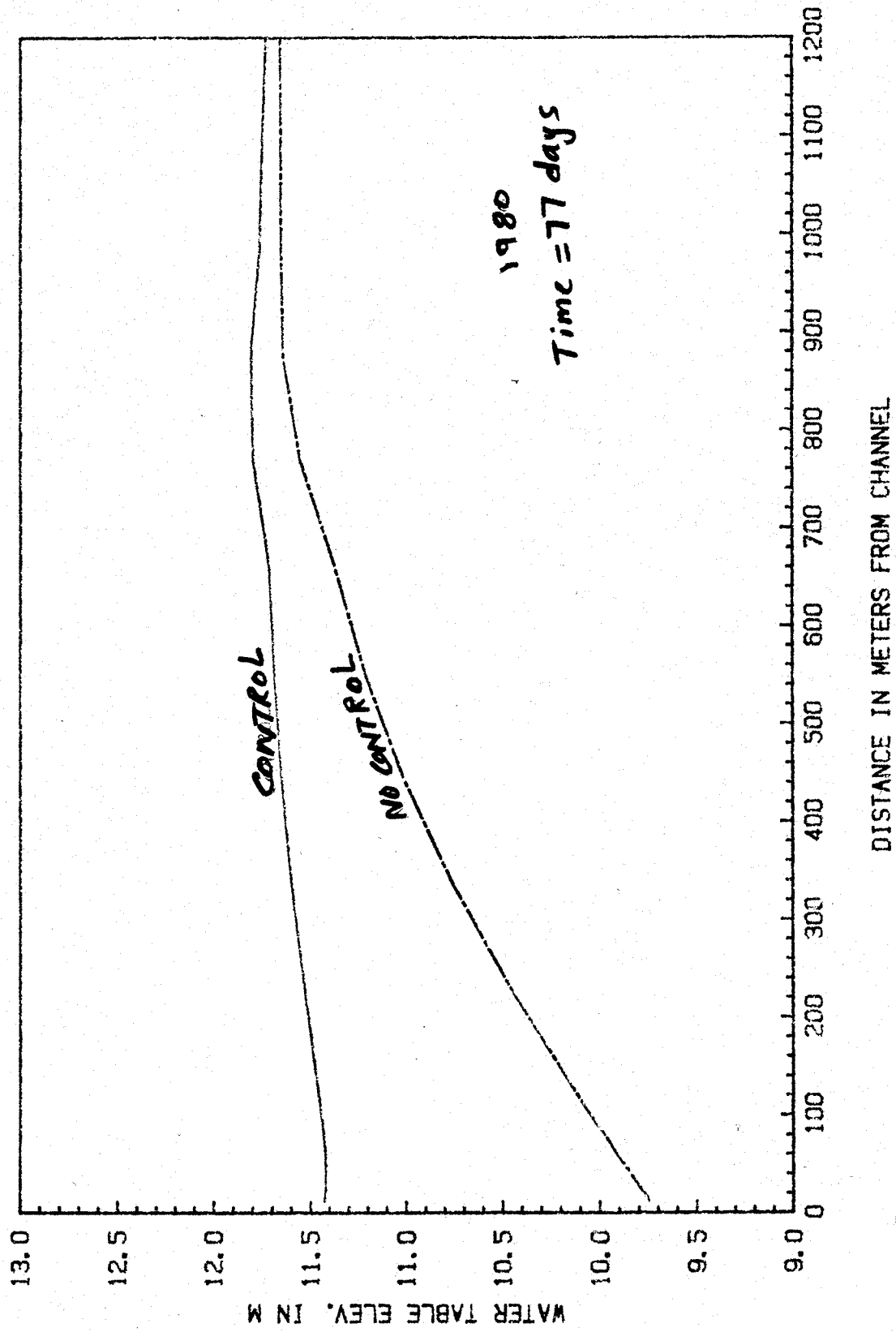
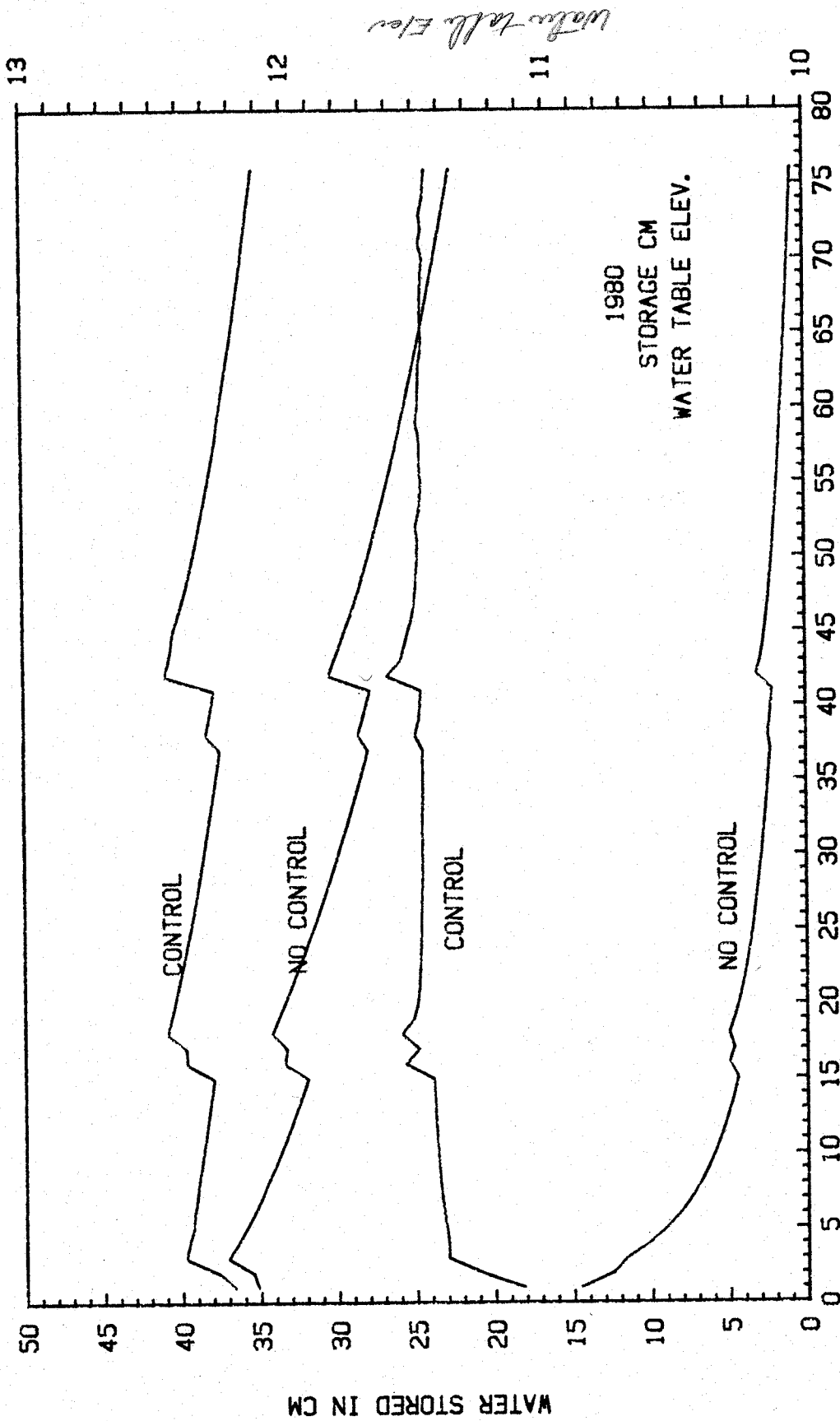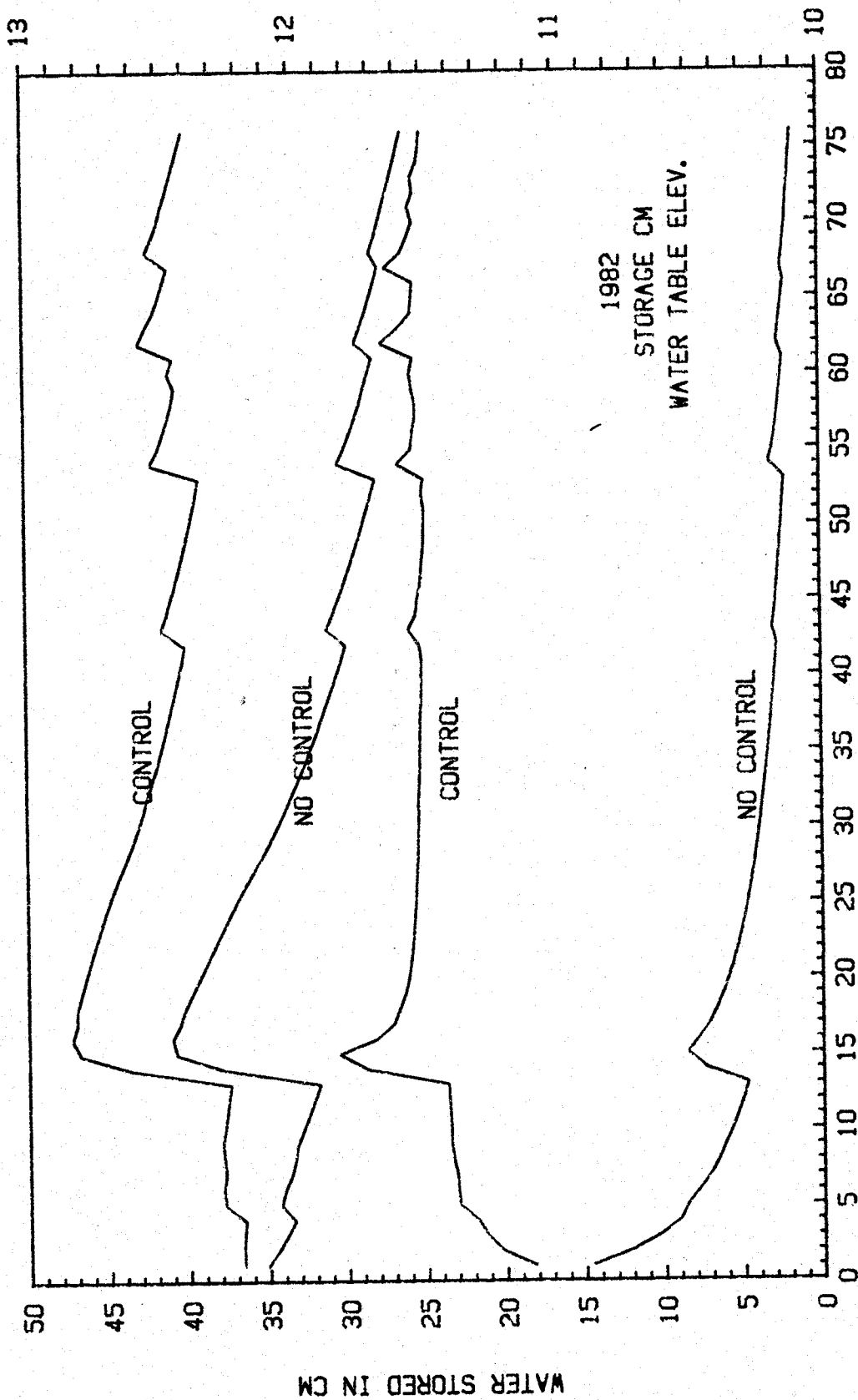Figure 7: Water table elevation from sea level versus distance from channell at end of 77 days simulation period

DISTANCE IN METERS FROM CHANNEL

WATER TABLE ELEV., IN M

1980
Time = 77 days

CONTROL

No CONTROL

Figure 8: The volume of stored water above the channel bottom elevation and water table elevation at 96m from the channel versus time

Figure 9: The volume of stored water above the channel bottom elevation and water table elevation at 96 m from the channel versus time

1982

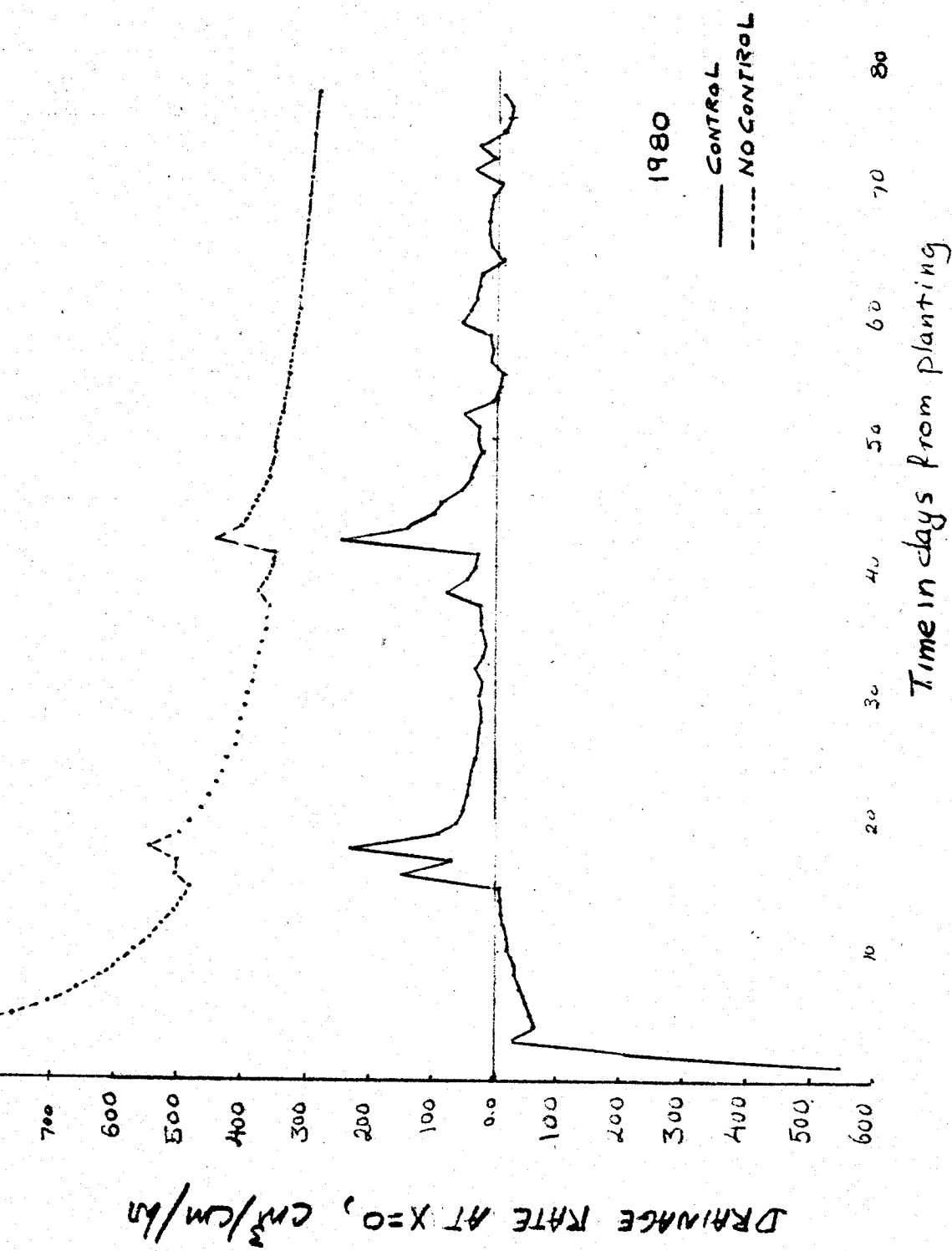STORAGE CM

WATER TABLE ELEV.

CONTROL

NO CONTROL

CONTROL

NO CONTROL

Time in days from planting

WATER STORED IN CM

Figure 10: Discharge rate into the channel versus time

DRAINAGE RATE AT X=0, cm³/cm/hr

Time in days from planting
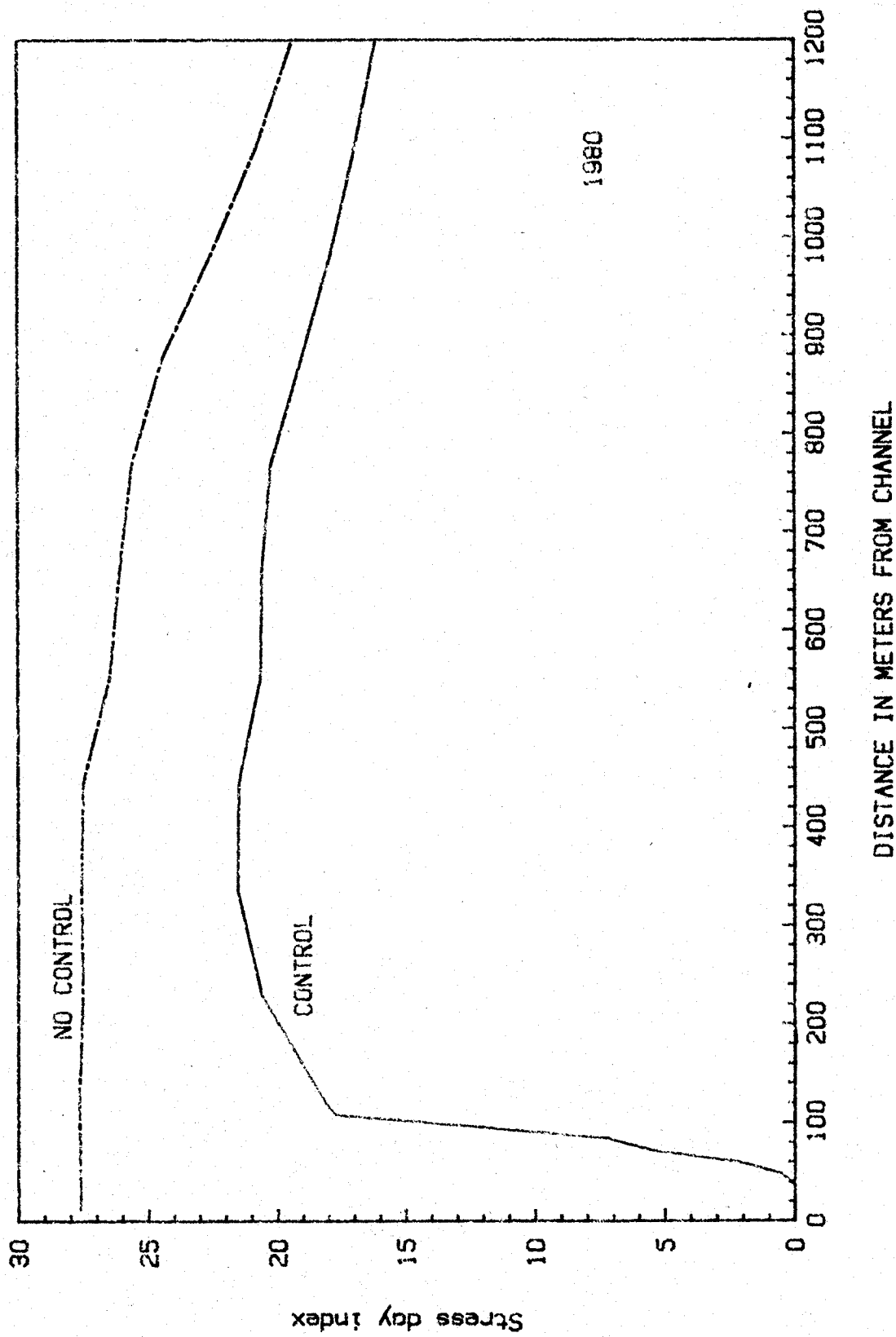
1980

CONTROL
NO CONTROL

Figure 12: ~~Stress day index vers~~ Accumulative stress day index versus time by the end of 77 days simulation period